A Comparison of Potential IM-CW Lidar Modulation Techniques for ASCENDS CO_2 Column Measurements from Space

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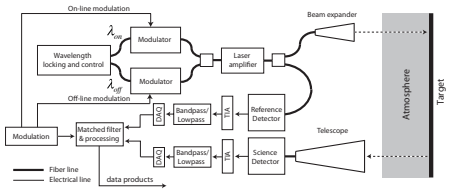
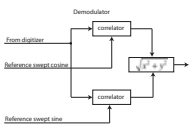
Abstract

Global atmospheric carbon dioxide (CO_2) measurements through the Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS) decadal survey recommended space mission are critical for improving our understanding of CO_2 sources and sinks. IM-CW (Intensity Modulated Continuous Wave) lidar techniques are investigated as a means of facilitating CO_2 measurements from space to meet the ASCENDS science requirements. In previous laboratory and flight experiments we have successfully used linear swept frequency modulation to discriminate surface lidar returns from intermediate aerosol and cloud contamination. Furthermore, high accuracy and precision ranging to the surface as well as to the top of intermediate clouds, which is a requirement for the inversion of the CO_2 column-mixing ratio from the instrument optical depth measurements, has been demonstrated with the linear swept frequency modulation technique. We are concurrently investigating advanced techniques to help improve the auto-correlation properties of the transmitted waveform implemented through physical hardware to make cloud rejection more robust in special restricted scenarios. Several different carrier based modulation techniques are compared including orthogonal linear swept, orthogonal non-linear swept, and Binary Phase Shift Keying (BPSK). Techniques are investigated that reduce or eliminate sidelobes. These techniques have excellent auto-correlation properties while possessing a finite bandwidth (by way of a new cyclic digital filter), which will reduce bias error in the presence of multiple scatterers. Our analyses show that the studied modulation techniques can increase the accuracy of CO_2 column measurements from space. A comparison of various properties such as Signal to Noise (SNR) and time-bandwidth product are discussed.

Instrument Concept



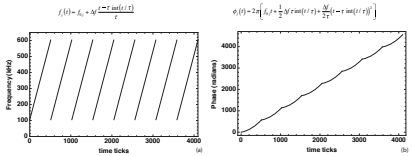
Linear Frequency Modulation



Frequency and phase

$$f_1(t) = f_{cc} + \frac{1}{2}M - \frac{M\sqrt{1-k^2}}{2}\cdot\frac{1-2r'\tau}{\sqrt{1-k^2}\left(1-2r'\tau\right)}, \quad \phi_1(t) = 2\pi\left[f_{cc}t + \frac{1}{2}Mt - \frac{M}{2\tau'}\left(1-\tau\sin(t/\tau)\right)\sqrt{1-k^2}\right]$$

$$\tau' = t - \tau\sin(t/\tau).$$

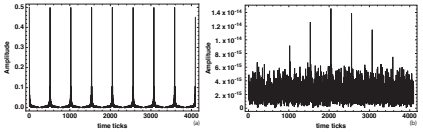


Example start freqiencies for orthogonal 8 sweep system with N=4096

$$f_{cc} = \frac{1450}{2\times8\times(512/2000)} - \frac{1}{2}500 = 104.004 \text{ kHz}, \quad f_{cc} = 104.004 \text{ kHz} + \frac{18}{2\times8\times(512/2000)} = 108.398 \text{ kHz},$$

$$f_{cc} = 104.004 \text{ kHz} + \frac{30}{2\times8\times(512/2000)} = 111.328 \text{ kHz}, f_{cc} = 104.004 \text{ kHz} + \frac{52}{2\times8\times(512/2000)} = 116.699 \text{ kHz}.$$

Autocorrelation function and cross-channel cross-correlation crosstalk

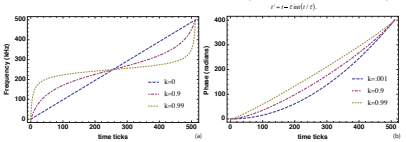


Non-linear Frequency Modulation for Lossless Sidelobe Suppression

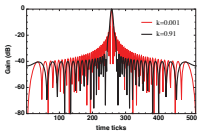
Frequency and phase

$$f_1(t) = f_{cc} + \frac{1}{2}M - \frac{M\sqrt{1-k^2}}{2}\cdot\frac{1-2r'\tau}{\sqrt{1-k^2}\left(1-2r'\tau\right)}, \quad \phi(t) = 2\pi\left[f_{cc}t + \frac{1}{2}Mt - \frac{M\tau\left(1-k^2\right)}{4\pi}\left(\frac{\left(1-k^2\right)\left(1-\frac{2t}{\tau}\right)}{\left(1-k^2\right)}\right)\right]$$

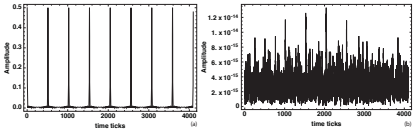
$$\tau' = t - \tau\sin(t/\tau).$$



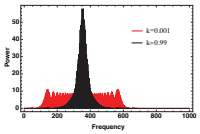
Mildly non-linear case results in moderate sidelobe suppression



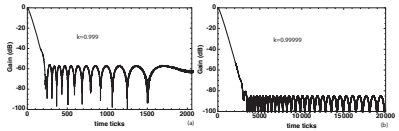
Autocorrelation function and cross-channel cross-correlation crosstalk (orthogonality preserved in non-linear case)



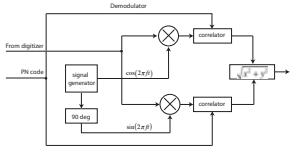
In the strong non-linear case, power spectrum has a Gaussian shape



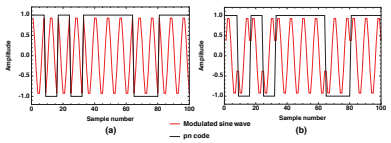
Sidelobe suppresion of 80 dB or more possible depending on the value of "k"



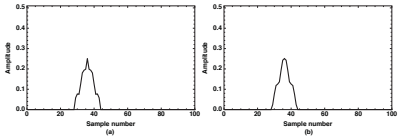
BPSK Modulation



BPSK modulation with 1 cycle per code bit

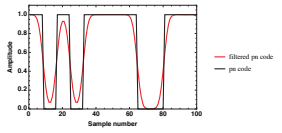


Autocorrelation function for cosine and sine case

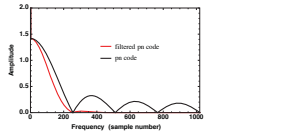


Filtered PN modulation

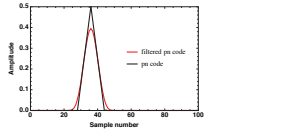
Filtered vs unfiltered PN code



Amplitude spectrum of filtered vs unfiltered PN code



Autocorrelation function for filtered vs unfiltered PN code



Circular Convolution filter based on Jacobi Theta Function of the Third Kind Results in Perfect Impulse Response Function

- No Sidelobes in Autocorrelation function
- Similar Resolution
- No aliasing issues at reasonable sample rates
- Closely Related to Guassian Filter

Define

$$W(n, L, q) = \vartheta_3(\pi n/L, q)/\vartheta_3(0, q)$$

Cyclic filter function is

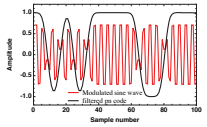
$$W(n-1, N, q)$$

To filter F with circular convolution

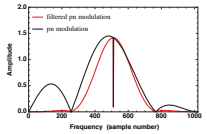
$$F' = DFT^{-}\left[W(n-1, N, q)\,DFT\left[F\right]\right], 1 \le n \le N$$

BPSK with Filtered PN

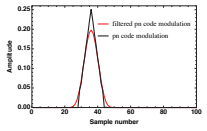
BPSK modulation with filtered PN code using 2 cycles per code bit



Amplitude spectrum for filtered vs unfiltered BPSK modulation



Autocorrelation function for filtered vs unfiltered BPSK modulation



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